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THERMOACOUSTIC HEAT TRANSPORT:

ANTHONY A. ATCHLEY

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Annual Summary for Period October 1992-September 1993.

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ABSTRACT

This annual report details progress in basic research in thermoacoustic heat transport made during the period October 1, 1992 through September 30, 1993. Our major research efforts in FY 1993 were concentrated in five areas: 1) an analysis of the initial buildup of oscillations in thermoacoustic prime movers; 2) an investigation of stability curves for a thermoacoustic prime mover, 3) initial measurements of the velocity field in thermoacoustic engines using laser Doppler anemometry, 4) measurements of heat exchanger performance in a thermoacoustic prime mover, and 5) a preliminary investigation of heat driven refrigerators. In addition to these areas, FY 1993 research efforts also included a collaborative experiment on traveling wave thermoacoustic effects. A brief review of the motivation behind these studies and a summary of the important results are contained in this technical report. A publications, patents, presentations, and honors report is also included.

BACKGROUND

The central theme of this research project has been that thermoacoustic heat transport phenomena are not well understood at high acoustic amplitudes. That this central theme is still true has been most recently confirmed in Ref. 1. In that work, Swift presents an extensive set of measurements of the performance of a large thermoacoustic prime mover. He uses a steady state, energy balance technique based on linear theory to calculate the steady state parameters of his engine. A heat input is specified, in watts, for the system. This heat input is converted to an acoustic power output according to thermoacoustic theory. Specifying the input in real units yields a dimensional, rather than nondimensional, calculated acoustic output. Swift observes significant discrepancies between the predicted and measured performance, especially at high amplitudes. Pippard[2] points out that the factors that determine the steady state amplitude of a spontaneously oscillating, such as a prime mover, may ultimately be nonlinear. Therefore, it is not surprising that discrepancies are observed. These nonlinearities may be attributed to different physical phenomena associated with prime movers. Three candidates from a ***nonexhaustive*** list immediately come to mind. They are harmonic generation, velocity dependent effects, and heat exchanger performance.

We[3] and, independently, Swift[1] have addressed harmonic generation previously. The current level of understanding of the role of harmonic generation in high amplitude acoustic standing waves is generally sufficient for us to mitigate its effects in thermoacoustics. Therefore, we turn to other limiting factors. Experimental evidence that some acoustic velocity dependent effect (such as acoustic streaming, vortex shedding, or turbulence) may influence acoustic heat transport was pointed out early on in our research.[4] To investigate velocity dependent effects further, we have initiated laser Doppler anemometer studies of the velocity field in thermoacoustic engines.

The role of heat exchange is paramount in thermoacoustics and there are a number of basic research issues related to it. There is evidence that *the* limiting factor accounting for the observed steady state amplitudes in prime movers is inadequate heat exchanger performance.[5] One manifestation of inadequate heat exchangers is the finite capacity for transferring heat into the engine from an external heat source. Limitations in available power input may not seem at first to be a nonlinear mechanism. However, it is in the same sense that a finite power supply output voltage level provides the nonlinearity that limits the amplitude of a spontaneously oscillating electrical circuit. The growth rate of the transient buildup of oscillations changes abruptly when the circuit output voltage reaches the power supply limits - the output clips. As long as the thermal-to-acoustic conversion involves only linear processes, the linear, steady state energy balance approach discussed earlier works. However, if nonlinear processes are involved, the calculations may have to be altered to take into account the transient part of the solution. Knowing at what acoustic levels various processes become important then becomes critical knowledge.

If it turns out that heat exchanger performance is the limiting factor, then only after the limitations are eliminated can other, perhaps more fundamental, limiting factors be investigated. If heat exchanger performance is not now the prime limiting factor, then it is likely to become so when the current limiting factors are better understood and their effects lessened or when required heat loads increase. Currently, thermoacoustic refrigerators handle heat loads of the order 10^2 W. However, heat loads of the order 10^4 W are required for Navy refrigeration and cooling purposes. Heat loads of this magnitude place thermoacoustics in a completely unexplored regime. We are currently investigating heat exchanger performance in high amplitude sound fields generated by a prime mover. This work in performed in collaboration with Prof. Thomas Hofler. It is expected that knowledge gained from prime mover experiments will be directly transferable to refrigerator technology.

This background has centered around prime movers. However, it is important to keep in mind that much of what is learned about prime movers can be carried over to improve thermoacoustic refrigeration and cooling technology.

SUMMARY OF PROGRESS

1) Analysis of the Initial Buildup of Oscillations in a Thermoacoustic Prime Mover

As discussed earlier, predicting the steady state amplitude of acoustic oscillations in prime movers is one of the fundamental questions yet to be fully answered about thermoacoustics. The purpose of this research is to address some issues related to the transition to steady state above onset. In particular, we analyze the initial buildup of oscillations in a prime mover and track the quality factor Q of a prime mover through onset. Full details of this work can be found in Ref. 6.

The transition to onset in a prime mover is conveniently discussed in terms of its Q. The acoustic power $\dot{W}$ generated by a prime mover can be related to Q through the relationship

$$Q = -\frac{\omega E_{ST}}{\dot{W}}. \tag{1}$$

A typical prime mover is comprised of five sections: the ambient duct, the ambient heat exchanger, the prime mover stack, the hot heat exchanger, and the hot duct. $\dot{W}$ is the sum of the power output of the five individual sections of the prime mover;

$$\dot{W} = \dot{W}_{amb} + \dot{W}_{amb\,hx} + \dot{W}_{pms} + \dot{W}_{hot\,hx} + \dot{W}_{hot}. \tag{2}$$

The subscripts *amb*, *amb hx*, *pms*, *hot hx*, and *hot* refer to the ambient duct, the ambient heat exchanger, the prime mover stack, the hot heat exchanger, and the hot duct, respectively. $\dot{W}$ is defined such that it is positive when power is generated. Q is typically expressed in terms of *dissipated* power, which is defined so as to be positive when power is lost. Because we are interested in power generation, we use $\dot{W}$ and introduce a minus sign in Eq. (1). E_{ST} is the stored acoustic energy and ω is the angular frequency of the oscillations.

All the terms on the right-hand side of Eq. (2) are inherently negative (representing dissipation) except for $\dot{W}_{pms}$. $\dot{W}_{pms}$ can be either positive or negative, depending on the temperature difference ΔT imposed across the stack and its position in the standing wave. As ΔT increases from zero, the thermal losses in the stack decrease. Hence, the net losses in the prime mover, consisting of thermal and viscous wall losses in each of the five sections (neglecting attenuation in the gas) decrease. The Q increases. As ΔT *increases further, the thermal* losses in the stack decrease to zero and then become negative, representing gain. At some higher ΔT, the thermal gain in the stack exactly balances the losses in the stack and $\dot{W}_{pms} = 0$. However, $\dot{W}$ is still negative, due to the other four terms in Eq. (2), and so Q is positive and finite. At a sufficiently high ΔT, the thermal gain overcomes all the losses and $\dot{W} = 0$. At this point Q is infinite, the net loss in the prime mover zero. The prime mover is in a state of unstable equilibrium. Any infinitesimal increase in ΔT will make $\dot{W}_{pms} > 0$, the net loss and Q negative; the prime mover will go into spontaneous self-oscillation. The complete evolution of Q as just described has never been previously demonstrated in the literature for an individual prime mover.

Regarding the question of what determines the steady state amplitude above onset, Pippard states that "non-linearity is . . . an ultimately inevitable feature of a spontaneously oscillating system."[2] The implication is that the factors determining the

steady state amplitude in a prime mover may not be contained in linear thermoacoustic theory. If one uses linear acoustic theory to derive an expression for Q, one finds that the result is independent of the acoustic pressure amplitude. Therefore, according to linear theory, once Q is finite-negative it will remain so regardless of the pressure amplitude in the prime mover. Therefore, because $Q = \infty$ at steady state, steady state can never be reached according to linear theory. However, steady state oscillations are observed in prime movers. Therefore, the states $(Q = \infty)_{onset}$ and $(Q = \infty)_{steady\ state}$ are fundamentally different.

One step along the path to understanding the factors that govern steady state is to analyze the initial buildup of oscillations in a prime mover above onset. During the initial buildup, the acoustic amplitudes are low and most of the complicating factors can be neglected. Analysis of the buildup and, in particular, at what amplitudes deviations between theory and measurement begin may help to identify particular mechanisms.

Previously,[7] we have discussed the evolution of Q up to onset. This work extends our investigation of prime movers through onset. The present measurements, coupled with previous ones (reported in Ref. 7) show the complete evolution of Q . We also find that the *initial* buildup of oscillations above onset is consistent with linear theory. It is shown that the results are consistent with predictions based on a standing wave analysis of thermoacoustics.[7]

2) Stability Curves for a Thermoacoustic Prime Mover

The onset of self-oscillation in prime movers can be considered in terms of a transition from a stable state to an unstable state. The stable state, below onset, is one for which the prime mover as a whole has a net positive damping. Any oscillations excited in a prime mover below onset decay in time. The unstable state, above onset, is one for

which the damping is negative. Oscillations at the resonance frequency initially exhibit exponential growth in amplitude. Eventually steady state is obtained and the growth rate is zero. The steady state acoustic pressure amplitude is typically on the order of a few percent or more of the mean gas pressure.

For a given prime mover geometry, mode and gas type, the temperature difference ΔT required for onset ΔT_{onset} is a function of the mean gas pressure P_m. A plot of ΔT_{onset} versus P_m defines the so called stability curve for a prime mover. Two such curves are shown in Fig. 1. The dashed (dash-dot) curve corresponds to the fundamental (second) mode. In order for self-sustained oscillations to exist, both parameters ΔT_{onset} and P_m must lie within the region of instability, above the curves in Fig. 1.

An extensive series of investigations on the behavior of simple prime movers (although they didn't call them that) was conducted by Yazaki, et al.[8-10] Their prime movers consisted of U-shaped stainless steel tubes (inner radius 1.2 - 4.7 mm, length 1.5 m and greater). The temperature of the lower part of the U was adjusted by a continuous flow of cold helium gas. The upper part of the U was maintained at room temperature (293 K). They investigated both the limits of stability of their system as well as the highly nonlinear nature of the oscillations above onset. They discovered a wealth of complex behavior, including phase locking, mode competition, quasiperiodicity and chaos.

We have undertaken a similar investigation on a practical prime mover. In particular, we have concentrated on the excitation of the second longitudinal mode of the prime mover and the simultaneous excitation of both the fundamental and second modes. The region of two mode excitation in practical prime mover has received little attention previously. The results are summarized below. Full details can be found in Ref. 11.

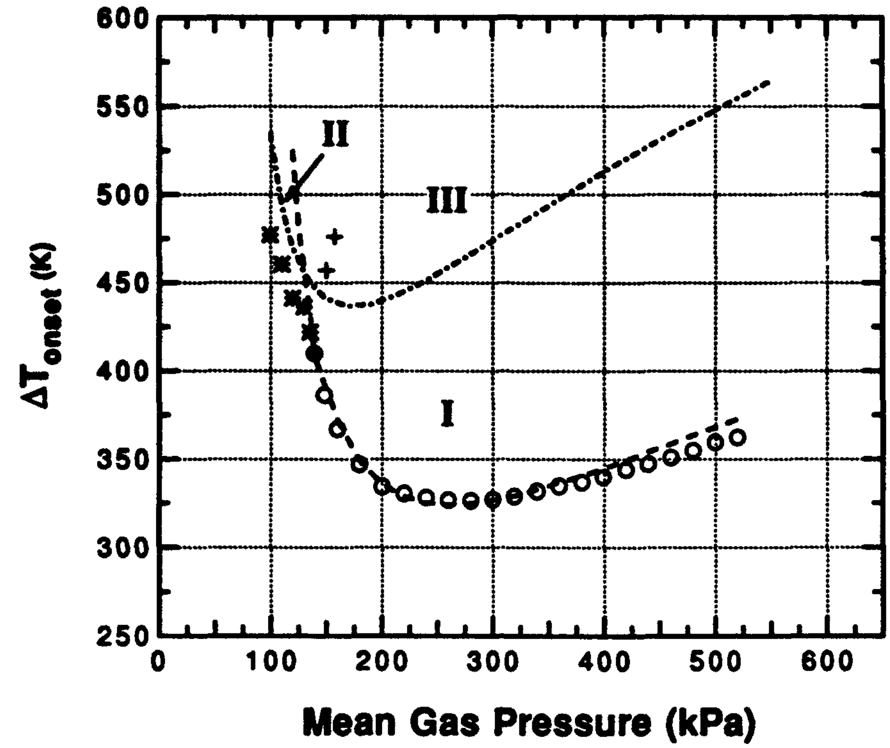

Figure 1

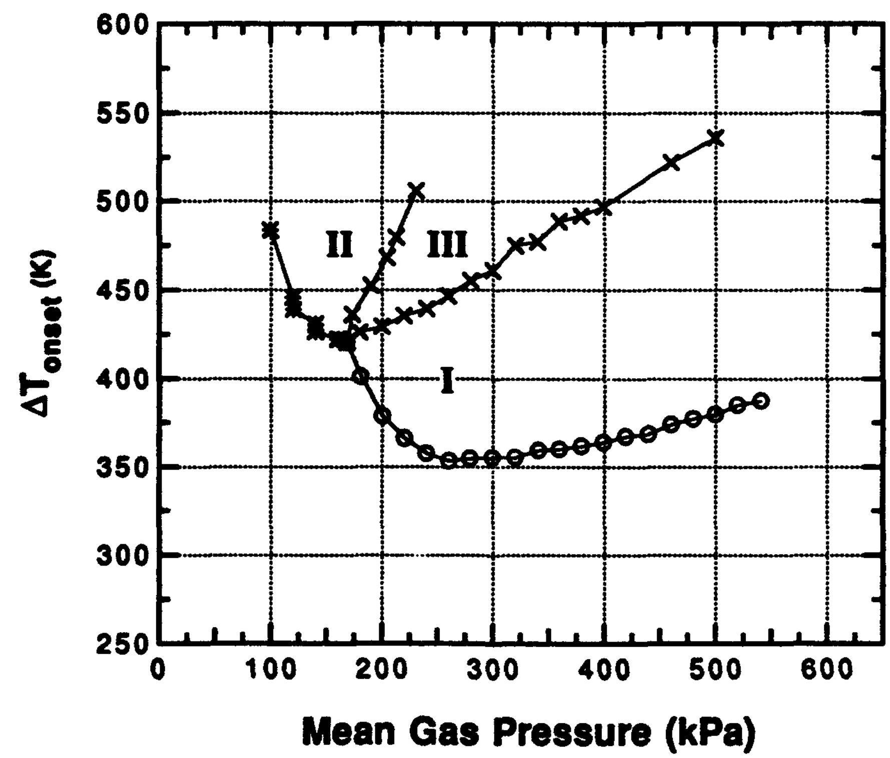

Figure 2

The measured stability curves for the fundamental and second modes of the prime mover are indicated by the symbols in Fig. 1. The o's indicate the measured onset conditions for the fundamental mode. The *'s indicate the measured onset conditions for the second mode. The +'s indicate the onset conditions for the fundamental mode, after the second mode is above onset. These last data points were obtained by fixing ΔT and increasing P_m. We estimate that the maximum error is ±5 K for ΔT_{onset} and ±1 to 2% for P_m. It is seen that the predicted and measured stability limits are in reasonable agreement for the fundamental mode at most mean pressures. The predicted trend for the second mode is consistent with the measurements, yet the predicted values of ΔT_{onset} are higher than those measured. The reason for this discrepancy with the second mode is not known, but is consistent with results reported in Ref. 2.

There are, however, two more interesting aspects of Fig. 1. The first is that the slope of the measured stability curve for the fundamental is positive when the second mode is excited. (These points are represented by the +'s.) The predicted slope of the stability curve at low pressures is negative. It is not completely surprising that the slope is different than that predicted because the theoretical curves do not take into account the presence of other modes. Apparently the presence of the second mode does, in fact, affect the stability of the fundamental. Note that the slope of the measured low pressure stability limit of the second mode is negative, as predicted. Also note that the second mode is the only one present in this region. In other words, there is no other mode present to interfere with it. One possible interaction is that the presence of the second mode alters the temperature distribution in the stack significantly, so that ΔT is unrepresentative of the actual conditions in the stack. Another possible explanation is that there is nonlinear mode competition between the fundamental and second mode. When the second mode is present, it has the advantage over the fundamental well into the region where the fundamental should be unstable. The behavior of the stability curve of

the fundamental at low pressures shows that below approximately 140 kPa, the fundamental mode will never be excited, regardless of how high ΔT becomes! This result is unexpected.

It is also observed that one mode can suppress the other. This is the second interesting aspect of Fig. 1 mentioned above. The measured stability curve for the second mode does not extend to the right of the intersection with that of the fundamental. In other words, we never observe onset of the second mode once the fundamental is excited. Two methods were used to search for second mode onset. In one, P_m was fixed and ΔT increased up to a maximum value of approximately 550 K, well above that which should be required for second mode onset. In the other case, we fixed ΔT and increased P_m. In neither case did the second mode reach onset.

Equally interesting is what happens to the second mode when the fundamental mode reaches onset. To use a specific example, if ΔT is set to 450 K and P_m is increased from zero, the second mode reaches onset at a pressure of approximately 115 kPa. As P_m is increased further, the amplitude of the second mode increases. When the mean pressure reaches approximately 150 kPa, we see the fundamental mode begin to grow. For a brief period, both modes are simultaneously excited with the amplitude of the fundamental increasing and that of the second mode decreasing. Soon, the second mode is completely gone and only the fundamental remains. Further increase of P_m only results in the growth of the fundamental. The second mode never comes back, even though it should be unstable.

To investigate this behavior further, we decided to selectively inhibit the fundamental mode, without affecting the second. This is accomplished by inserting an annular disk in the prime mover at the location of the velocity antinode of the fundamental mode. The 3.13-mm thick brass disk has a 18.3 mm diameter hole in the center. The idea is that the reduced cross section presents a significant flow impedance to

the fundamental mode, thereby raising its ΔT_{onset}. But, because the disk is near the velocity node of the second mode, the second mode onset conditions will be affected very little. By inhibiting the fundamental, the fundamental's influence on the second mode should be diminished.

The stability curves for the modified prime mover are shown in Fig 2. The symbols have the same meaning as in Fig. 1. The solid lines simply connect the data points and serve as guides to the eye. Several points are immediately evident. First, the left branch of the stability curve for the second mode is unaltered by the presence of the disk. However, the stability curve for the fundamental shifts toward higher ΔT and P_m. In addition to shifting the stability curve, the disk also results in a much lower fundamental amplitude. This apparently allows the second mode to dominate over the fundamental to a larger extent, as indicated by region II occupying more parameter space in Fig. 2 than in Fig. 1. Second, the stability curve for the second mode now extends into the region where the fundamental mode previously dominated. The reduced fundamental amplitude apparently prohibits it from quenching the second mode. In the region labeled III, both modes are simultaneously excited and coexist in steady state.

We recorded waveforms for the modified prime mover at ΔT equal to 450 K and mean gas pressure of 150, 240 and 440 kPa. These parameters place us in regions I, II and III of Fig. 2. The waveforms for the points (P_m, ΔT) = (150 kPa, 450 K) and (440 kPa, 450 K) show that only one mode (the second and fundamental, respectively) is excited. The situation is different at the point (240 kPa, 450 K) in region III. In this region both modes are excited simultaneously. Spectral analysis reveals that the frequency of the fundamental mode is 484.0 Hz and that of the second mode is 996.1 Hz. Because the fundamental and second modes are not harmonic, the second mode is easily distinguished from harmonics of the fundamental mode. More importantly, it means that the combination is not periodic. It is quasiperiodic.

The results of this work point to several areas for further work. First, there is need for a model that accurately predicts the stability curves by accounting for the interaction between modes. Also, measurements of the stability curves in parameter regions where both modes exist may prove to be a useful testbed for various thermoacoustics models. The use of a series of discs with progressively larger holes and progressively larger fundamental amplitudes might be useful in studying the reported effects in more detail. Finally, a more extensive investigation of (P_m, ΔT) parameter space may reveal regions of more complex behavior. Such a study may lead to novel applications regarding the control of oscillations in prime movers.

3) Initial Measurements of the Velocity Field in Thermoacoustic Engines Using Laser Doppler Anemometry

As discussed in the Background section, we have initiated an investigation of the velocity field in thermoacoustic engines using a laser Doppler anemometer (LDA). These preliminary measurements consist of probing the velocity field in an acoustic resonator driven with a high intensity compression driver.[12,13] The first set of measurements consisted of measuring the acoustic velocity amplitude at a velocity antinode as a function of the acoustic pressure amplitude. The velocities were converted to pressures using the standard value of specific acoustic impedance for air (415 kg m^{-2} s^{-1}). A graph of the so called "derived pressure" versus the actual measured pressure is shown in Fig. 3. The solid line is a least squares fit to the data. The slope of the fit is 0.997. Data was obtained for pressures ranging from 20 to 4000 Pa. (4000 Pa was about the most we could get from our driver without blowing the voice coil.) We also measured the velocity as a function of position along the axis of the resonator at a fixed pressure amplitude. The results show the expected sinusoidal variation.

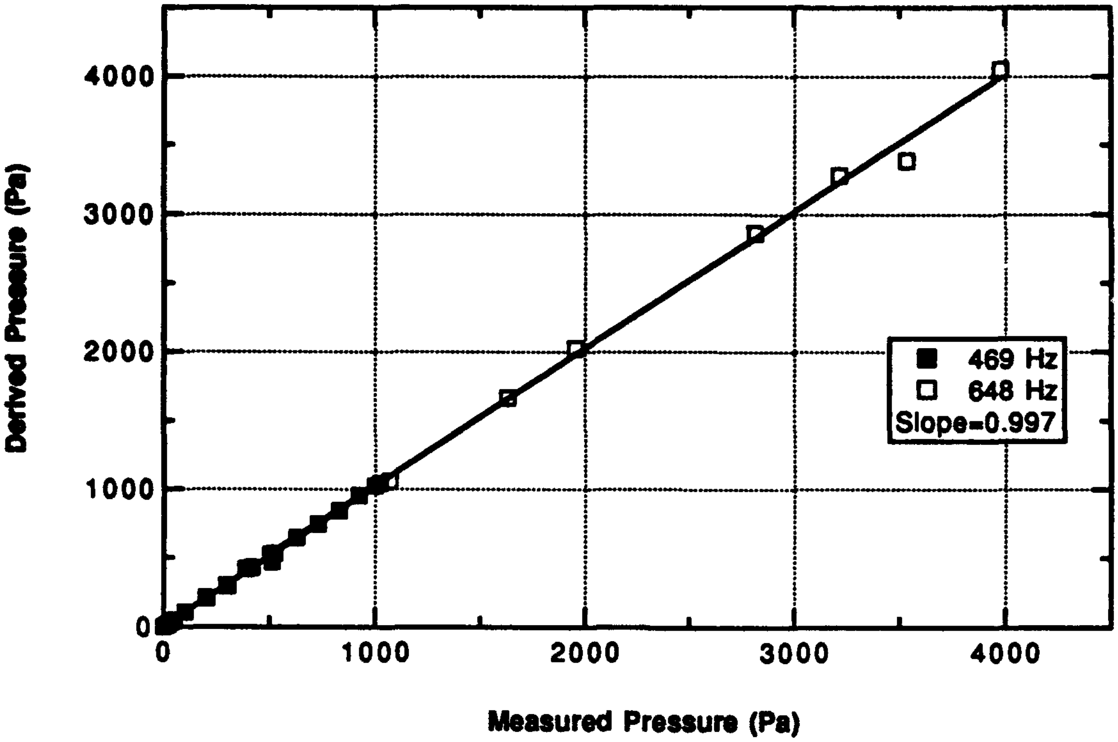

Figure 3a

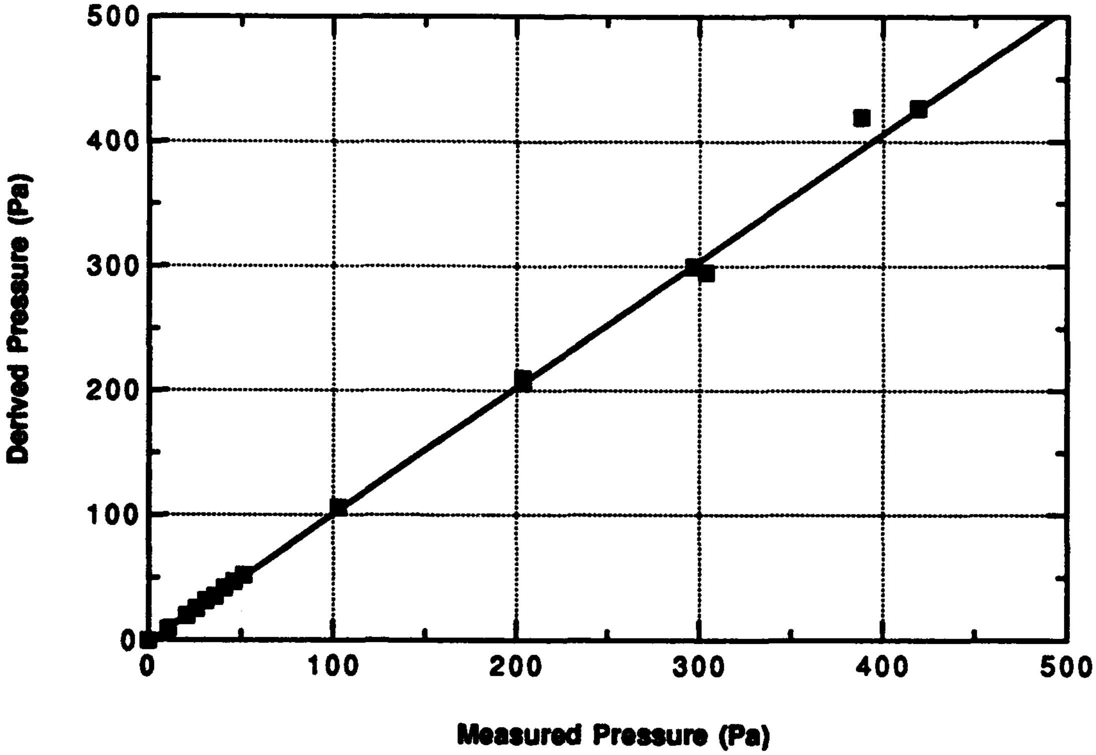

Figure 3b

Figures 4 and 5 show the acoustic velocity and acoustic pressure as functions of time for two pressure amplitudes. It is seen that at low amplitudes the two waveforms overlap. This is expected if one is in the linear acoustic regime. At higher amplitude, Fig. 5, harmonics appear in both waveforms. Analysis of the amplitudes of the harmonics should yield the nonlinear coefficient of the gas.

Finally, we put a simple stack constructed from microscope slides in the resonator and made measurements at various distances from the stack entrance. The results are shown in Fig. 6 for three different pressure amplitudes. Negative positions are outside the stack, the edge is at zero and positive positions are inside the stack. The dashed lines represent the change in velocity expected from the change in cross section and position in the standing wave.

These preliminary measurements indicate that LDA is a useful tool in probing the velocity field. They also show that, at least in the parameter range covered, no significant perturbations in fluid velocity on acoustic time scales are apparent. We have made a video tape of flow processes in the resonator which shows significant activity, albeit at slower time scales. We intend to investigate these time scales more in the future.

4) Measurements of Heat Exchanger Performance in a Thermoacoustic Prime Mover

This research is being done in collaboration with Prof. Thomas Hofler and Dr. David Gardner. To assess heat exchanger performance we have built a modular prime mover which allows installation of different heat exchangers without altering the geometry of the remainder of the prime mover. The prime mover is designed to operate between room temperature and liquid nitrogen temperatures. The working substance is

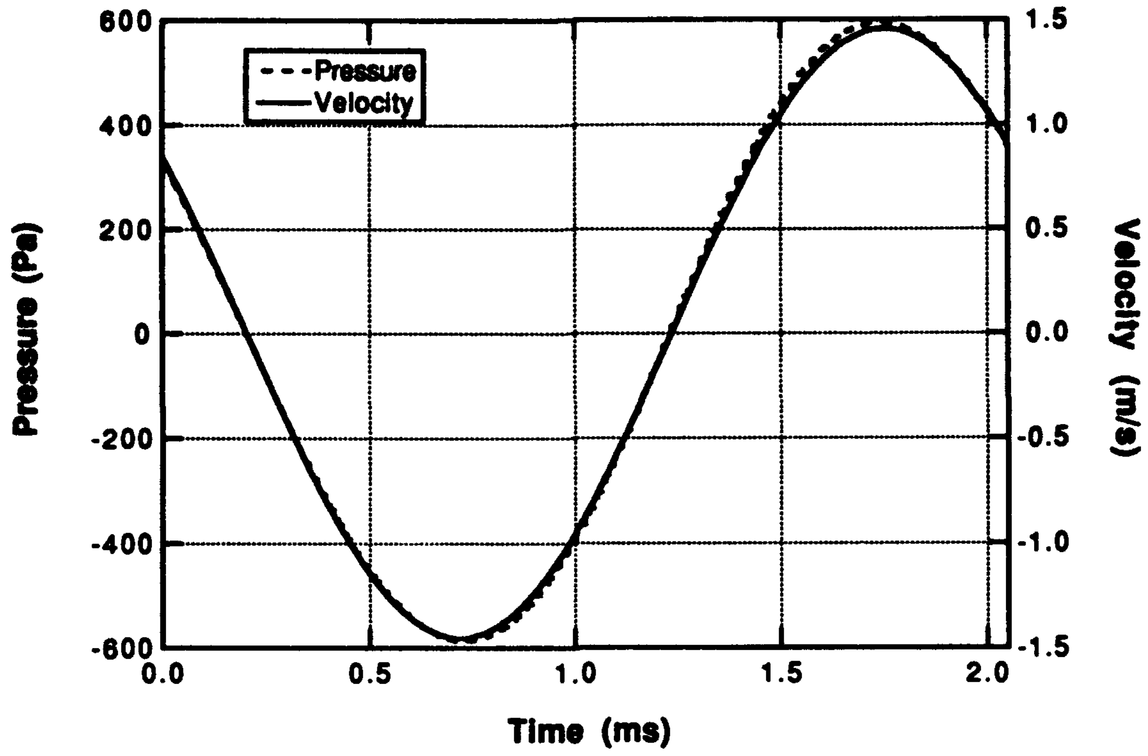

Figure 4

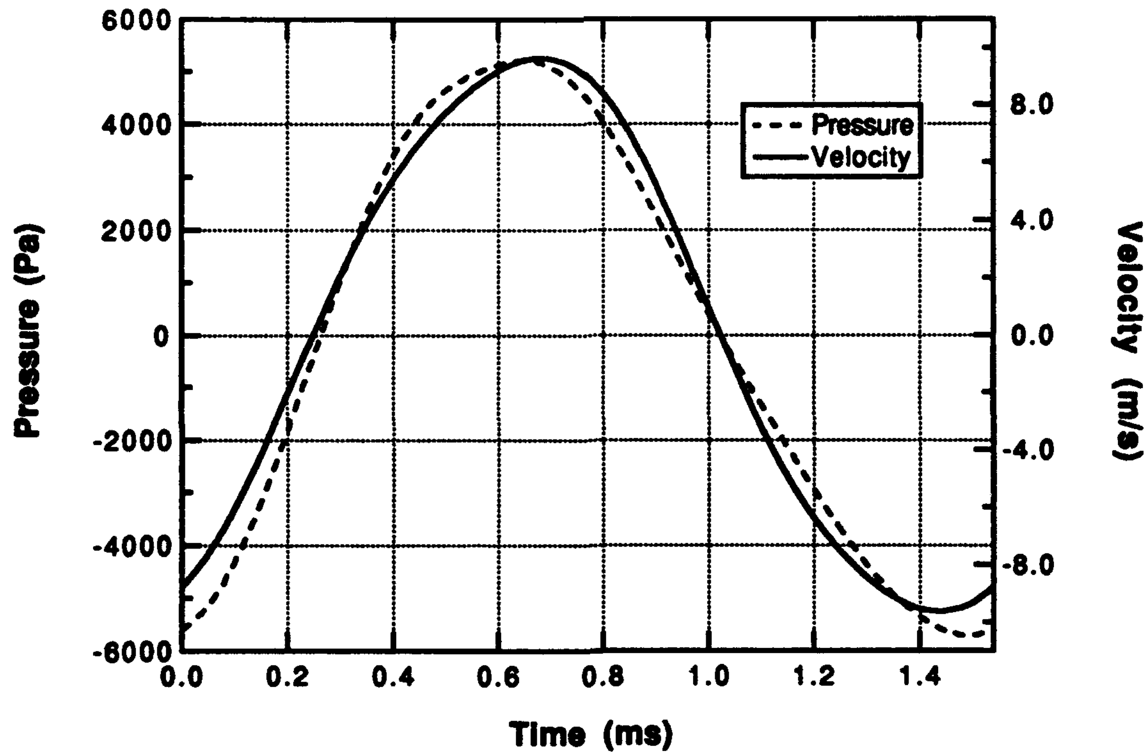

Figure 5

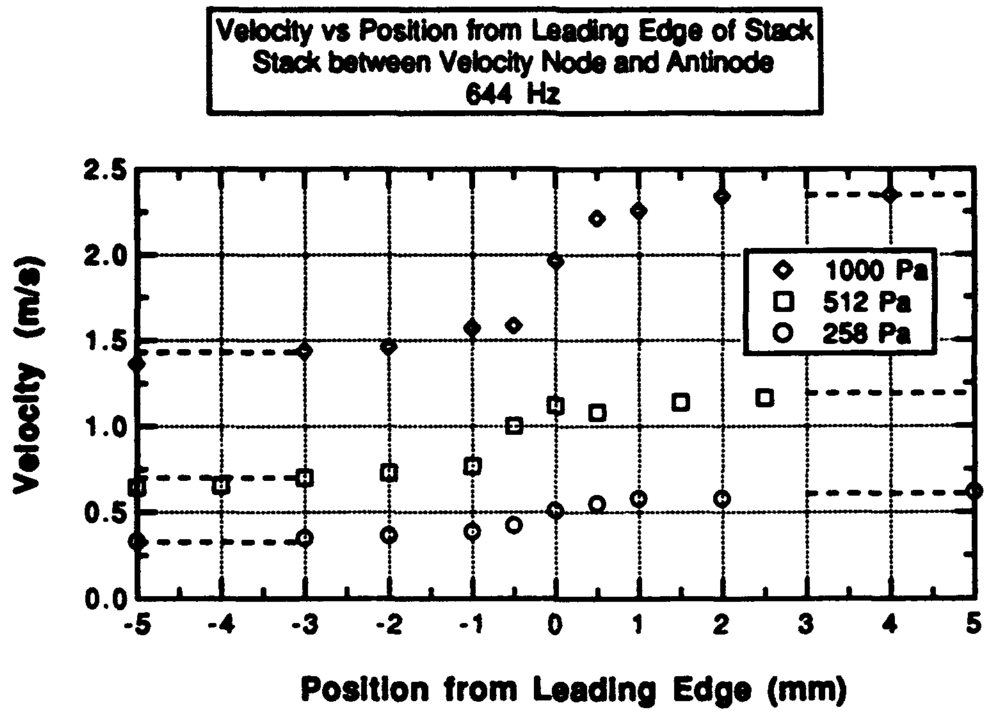
Velocity vs Position from Leading Edge of Stack
Stack between Velocity Node and Antinode
644 Hz
Velocity (m/s)
2.5
2.0
1.5
1.0
0.5
0.0
-5
-4
-3
-2
-1
0
1
2
3
4
5
Position from Leading Edge (mm)
1000 Pa
512 Pa
258 Pa

Figure 6

neon. The hot end of the prime mover is fitted with a movable piston which allows us to vary the position of the thermoacoustic elements (stack and heat exchangers) relative to the standing wave. The prime mover is instrumented with several thermocouples which permit measurement of the temperatures of the hot and cold ends of the resonator, the temperature of the hot and cold heat exchangers both near the wall of the resonator and near the center of the heat exchanger (along the axis of the resonator), and the temperatures of the hot and cold ends of the stack near the stack/heat exchanger junction. Knowledge of the temperature distribution in the transverse direction in the heat exchanger (perpendicular to the resonator axis) allows calculation of the heat flow into or out of the heat exchanger. Knowledge of the temperature difference across the stack/heat exchanger junction provides information about the acoustic heat transport across the junction.

We have completed an initial set of measurements.[14,15] The important results are: 1) acoustic pressure amplitudes as high as 29% of mean gas pressure were generated in the prime mover; 2) short heat exchangers performed better than might have expected from simple, boundary layer arguments; 3) peak-to-peak displacement amplitudes as much as 10 times the heat exchanger length were achieved; and 4) peak-to-peak displacement amplitudes equal to the stack length (2.5 cm) were achieved. Such large displacements are not easily handled by standard thermoacoustic theory, which assumes small displacements compared to the stack length.

5) Preliminary Investigation of Heat Driven Refrigerators

Investigation of heat driven thermoacoustic refrigerators has been one of the long term goals of our research program. The development of a refrigerator is certainly more applied than most of our previous work. But, because a heat driven refrigerator consists

of both a prime mover and a heat pump, it constitutes a much more demanding test of our understanding of thermoacoustics. Although, Wheatley built a prototype device (with which he was able to achieve cold end temperatures below 0 °C) shortly before his death, there has been little subsequent work on this type of device.

During FY 1993, we began a collaboration, through an IPA, with Dr. Pat Arnott at the Desert Research Institute to adapt his thermoacoustic modeling techniques to handle heat driven refrigerators. At this point, Dr. Arnott has finished writing the code and has done some optimization analysis[16]

6) Traveling Wave Thermoacoustic Effects

Colleagues at the University of Mississippi (Profs. Richard Raspet and Henry Bass) have become interested in traveling wave thermoacoustic effects. They developed a theory that shows that the traveling wave phasing between pressure and velocity leads to heat transport terms not contained in standing wave thermoacoustic theory.[17] Previously, we have considered the possibility of using a thermoacoustic device to terminate a traveling wave tube.[18] This mutual interest in traveling wave effects prompted us to perform a joint experiment with these colleagues. The experiment consisted of measuring the reflection coefficient of a thermoacoustic element as a function of frequency. One end of the element was maintained at room temperature, the other near liquid nitrogen temperatures. The results of the experiment are currently being analyzed.[19]

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17. R. Raspet, H. E. Bass and J. Kordomenos, "Thermoacoustics of traveling waves: Theoretical analysis for an inviscid ideal gas," J. Acoust. Soc. Am. 94, 2232-2239 (1993).

18. A. A. Atchley, "Annual Summary of Basic Research in Thermoacoustic Heat Transport: 1992," Naval Postgraduate School Report Number NPS-PH-93-006, 10-11 (1992).

19. J. Kordomenos, A. A. Atchley, R. Raspet, and H. E. Bass, "Thermoacoustic termination for a traveling wave tube," J. Acoust. Soc. Am. 94, No. 3, Pt. 2, 1773(A) (1993).

OFFICE OF NAVAL RESEARCH
PUBLICATION/PATENTS/PRESENTATION/HONORS REPORT
for
1 Oct 92 through 30 Sept 93

R&T Number: 4126949

Contract/Grant Number: N00014-93WR24008

Contract/Grant Title: Basic Research in Thermoacoustic Heat Transport

Principal Investigator: Anthony A. Atchley

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a. Number of Papers Submitted to Referred Journal but not yet published: 2

b. Number of Papers Published in Referred Journals: 2
(list attached)

c. Number of Books or Chapters Submitted but not yet Published: 0

d. Number of Books or Chapters Published: 0
(list attached)

e. Number of Printed Technical Report & Non-Referred Papers: 4
(list attached)

f. Number of Patents Filed: 0

g. Number of Patents Granted: 0
(list attached)

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 2

i. Number of Presentation at Workshop or Prof. Society Meetings: 8

j. Honors/Awards/Prizes for Contract/Grant Employees:
(list attached, this might include Scientific Soc. Awards/Offices, Promotions, Faculty Award/Offices etc.) 2

k. Total number of Graduate Students and Post-Docs Supported at least 25%, this year on this contract,grant:
Grad Students 0 and Post Docs 0

How many of each are females or minorities? (These 6 numbers are for ONR's EEO/Minority Reports; minorities include Blacks, Aleuts Amindians, etc and those of Hispanic or Asian extraction/nationality. This Asians are singled out to facilitate meeting the varying report semantics re "under-represented")

Grad Student Female	____
Grad Student Minority	____
Grad Student Asian e/n	____
Post-Doc Female	____
Post-Doc Minority	____
Post-Doc Asian e/n	____

P3H Report Continued
1 Oct 92 through 30 Sept 93

Refereed Publications

D. Felipe Gaitan and Anthony A. Atchley, "Finite amplitude standing waves in harmonic and anharmonic tubes," J. Acoust. Soc. Am. 93, 2489-2495 (1993).

Anthony A. Atchley, "Standing wave analysis of a thermoacoustic prime mover below onset of self-oscillation," J. Acoust. Soc. Am. 92, 2907-2914 (1992).

Non-Referred Papers

Anthony A. Atchley, "Review of recent advances in synchronous picosecond sonoluminescence," Advances in Nonlinear Acoustics, edited H. Hobaek (World Scientific, River Edge, NJ, 1993), pp. 36-41.

W. J. Lentz, Anthony A. Atchley, D. Felipe Gaitan, and X. K. Maruyama, "Mie scattering from a sonoluminescing bubble," Advances in Nonlinear Acoustics, edited H. Hobaek (World Scientific, River Edge, NJ, 1993), pp. 400-405.

J. T. Carlson, S. D. Lewia, Anthony A. Atchley, D. Felipe Gaitan, X. K. Maruyama, M. E. Lowry, M. J. Moran, and D. R. Sweider, "Spectra of picosecond sonoluminescence," Advances in Nonlinear Acoustics, edited H. Hobaek (World Scientific, River Edge, NJ, 1993), pp. 406-411.

Technical Reports

Anthony A. Atchley, "Annual summary of basic research in thermoacoustic heat transport: 1992," Naval Postgraduate School Report Number NPS PH-93-006, 32 pages, November, 1992.

Honors/Awards/etc.

1992 Naval Postgraduate School Research Recognition Award

Elected Chair of the Acoustical Society of America's Physical Acoustics Technical Committee

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